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VARACTOR DIODE INDUSTRIAL PREPAREDNESS
MEASURES

11TH QUARTERLY PROGRESS REPORT

25 December 1962 through 25 March 1963

Signal Corps Contract No. DA36-039 SC-85941

Signal Corps Technical Requirements No. SCS-63

Dated 21 September 1959

Signal Corps Supply Agency
225 South 18th Street
Philadelphia 3, Pennsylvania

MICROWAVE ASSOCIATES, INC.

Burlington, Massachusetts

DA36-039 SC-85941   11th Quarterly Progress Report
Microwave Associates, Inc.   25 December 1962 through 25 March 1963

Distribution List

SECTION I - PURPOSE

The purpose of this contract is the establishment of
a capability to mass-produce a variable capacitance microwave
diode. This diode, known as a "varactor diode", is a silicon
diffused mesa device.

SECTION II - ABSTRACT

A. A method for measuring the series resistance of a
varactor diode is presented. The measurement is based on a
determination of the transmission loss due to inserting a diode
in a shunt with a transmission line. The transmission loss, min-
imized by series tuning of the diode, is converted to series
resistance in ohms through use of a conversion graph.

B. A method for passivating the surface of silicon is
also presented describing the actual increase in production and
reliability through the use of this technique.

C. A new pill package style will also be discussed in
this report. This pill package, known as pill III, has allowed
the production of a more reliable finished semiconductor product.

SECTION III - PUBLICATIONS AND REPORTS

No publications connected with this contract were made
during the interval covered by this contract.

SECTION IV - FACTUAL DATA

A. R_s Measurement

This method of measuring varactor series resistance was suggested independently by R. Tenenholtz at Microwave Associates and A. E. Bakanowski at Bell Telephone Labs. The measurement method consists of shunting a transmission line with the varactor, and it has been adopted because of its convenience and reproducibility. The basic equation and the correction for finger losses in the adjustable stub are given here.

Consider a transmission line as in Figure 1, of characteristic impedance G_0 shunted by an arbitrary admittance Y. The generator current is i_g.

$$i_g = V (2 G_0 + Y)$$

$$i_L = V (G_0)$$

$$\frac{i_g}{i_L} = 2 + \frac{Y}{G_0}$$

$$\left(\frac{i_g}{i_L}\right)^2 = \left[2 + \frac{Y}{G_0}\right]^2$$

If $Y = 0$, $\left(\frac{i_g}{i_L}\right)^2 = 4$

∴ If $Y \neq 0$, transmission loss in power ratio is equal to

$$\frac{1}{4} \left|2 + \frac{Y}{G_0}\right|^2 = \left|1 + \frac{Z_0 Y}{2}\right|^2$$

where $Z_0 = \frac{1}{G_0}$

If $Y = \dfrac{1}{R_s}$

Transmission Loss, Power Ratio =

$$\left(1 + \frac{Z_0}{2 R_s}\right)^2$$

$(\text{Trans. Loss, Power Ratio})^{\frac{1}{2}} =$

"Trans. Loss, Voltage Ratio"

$= \text{T.L., V.R.}$

$\text{T.L., V.R.} = 1 + \dfrac{Z_0}{2 R_s}$

Solve for R_s

$$R_s = \frac{Z_0/2}{\text{T.L., V.R.} - 1}$$

$$R_s = \frac{25}{\text{T.L., V.R.} - 1} \qquad \text{if } Z_0 = 50 \text{ ohms}$$

If we now consider how to make a varactor diode look like a pure shunt R_s, and adjustable series inductance may be used to cancel the series capacitance as shown in Figure 2. If L is adjusted for minimum transmission (or maximum transmission loss), then

$$Y = \frac{1}{R_s}$$

The variable inductance can be an adjustable stub having sliding fingers as shown in Figure 3. The resistive loss RF of the sliding fingers contributes to the apparent series resistance measured above.

R' is apparent resistance at input of stub.

R' should be subtracted from measured resistance to get net series resistance of varactor.[1]

$R' \geq R_F$

R' can be calculated as follows.

The equivalent resistance of the stub may be calculated by stating at finger position, reflection coefficient = ρ_1 .

$$\rho_1 = \frac{R_F - Z_0}{R_F + Z_0} = - \frac{1 - R_F/Z_0}{1 + R_F/Z_0}$$

If $R_F \lll Z_0$ (approximation)

$$\left[\rho_1\right] \cong 1 - 2\frac{R_F}{Z_0}$$

$$1 - \left[\rho_1\right]^2 \cong 4\frac{R_F}{Z_0}$$

At input of line, reflection coefficient = ρ

$$\rho_2 = \frac{R' + jX - Z_0}{R' + jX - Z_0}$$

$$\left[\rho_2\right]^2 = \frac{(R' - Z_0)^2 + X^2}{(R' + Z_0)^2 + X^2}$$

$$1 - \left[\rho_2\right]^2 = \frac{4 R' Z_0}{(R' + Z_0)^2 + X^2}$$

But $\left[\rho_2\right] = \left[\rho_1\right]$ (assuming line is lossless)

Therefore,

$$4\frac{R_F}{Z_0} = \frac{4 R' Z_0}{(R' + Z_0)^2 + X^2}$$

$$\frac{R'}{R_F} = \left(\frac{X}{Z_0}\right)^2 + \left(1 + \frac{R'}{R_F}\right)^2$$

$$\cong \left(\frac{X}{Z_0}\right)^2 + 1 \quad \text{if } R' \lll R_F$$

[1] On the present contract, nothing is subtracted from the R_s measurement.

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When a short circuit is put in the diode socket, $X = 0$ and $R_F = R' =$ measured resistance.

B. Frequency Dependence of Series Resistance

There is an apparent frequency dependence of the series resistance of a varactor diode, but conclusive proof is difficult to obtain. The reason for this difficulty is that measurement errors tend to vary much more rapidly with frequency than does the series resistance. A recent letter by L. D. Braun [2] has reported a marked increase in series resistance at relatively low frequencies (320Mc), compared to the values measured above 2 Gc (Figure 4). Unfortunately, circuit losses were not treated quantitatively in these discussions, and the following calculations will show how easy it would be for circuit losses to lead to the published results.

In the measurement, "the reactance of the varactor at a particular bias was tuned out with a short-circuited stub in series with the varactor". The effect of a hypothetical small resistance R at the end of the stub (for example, resistance of sliding contact fingers) can be very severe in such measurements. Let X be the reactance exhibited by the stub and R' the transformed apparent resistance. Then, from the previous analysis,

$$\frac{R'}{R} \cong \left(\frac{X}{Z_o}\right)^2 + \left(1 + \frac{R'}{Z_o}\right)^2 \quad \text{for } R \ll Z_o$$

2 L. D. Braun " Frequency Dependence of the Equivalent Series Resistance of Varactor Diodes and its Effect on Parametric Amplification," PROC. I.R.E., vol. 50, pp 2523-2524 (Dec. 1962).

As long as R' is much less that R, the frequency-dependent part of the apparent resistance is given by

$$\frac{R' - R}{R} \cong \left(\frac{X}{Z_0}\right)^2$$

This explains Braun's results on the MA450HR and MA450FR.

C. <u>Passivation</u>

In this quarter a technique was developed to passivate the silicon surface in order to make for a more reliable product. Previous to the development of this technique, trouble was encountered in maintaining a clean surface on large area silicon epitaxial diodes. The overall yield on these types was extremely low, and a serious production problem developed. The reliability of these diodes was also in question because of the instability of the finished varactor diode.

A silane treatment was first selected on order to solve this problem. Diphenyldichloryl silane was applied to the surface of the silicon dice, but the results were not conclusive as the yield and instability problem were only partially alleviated. The overall yield increased slightly, but the instability remained. Another approach was taken when a silane was injected directly onto the silicon element after it had been inserted into the Style C package. This proved to be deleterious to the unit because the silane attacked the brass body and corroded the parts badly. Several varnishes and epoxies were painted onto the silicon surface without success. Finally, a silicon monoxide (SiO) procedure was

discovered and ultimately was the solution to the instability and yield problem. It was found by evaporating silicon monoxide onto the silicon surface at a pressure of 10-6 mm of Hg, that the overall yield increased substantially. The instability that was such a problem also disappeared because the silicon monoxide formed a protective layer on the silicon surface which protected it from any contamination. The silicon monoxide is applied directly after an HF-HNO$_3$ acid clean-up of the silicon surface, and this has led to a more stable and reliable varactor diode. It was also found that the silicon monoxide had to be applied immediately after the acid clean-up procedure in order to fully protect the silicon surface satisfactorily.

In conclusion, the silicon monoxide passivation technique increased the overall yield of the high capacitance varactor diodes. It has also increased the stability of the varactor diodes while the other passivation techniques that were tried only led to an increased instability. With this technique, the varactor diodes that are now being manufactured are of higher reliability than those produced before the silicon monoxide passivation treatment.

D. Pill III

A new pill package style has been incorporated to provide a more reliable finished semiconductor product (Figure 8). The features that the new package incorporates are:

(1) Bonded contact (elimination of "C" spring).

(2) Open type construction to allow for a greater ease of fabrication.

(3) Welded final seal to provide for a more hermetic package (NO soft solder).

The open package as shown in Figure 9 is purchased in assembled form as shown. Various contacting methods were evaluated in order to produce varactor diodes in this package style. The results of these evaluations are shown in Figure 10. The predecessor to pill III is shown in Figure 11, and it was called pill II. Pill II used the old push pin techniques discussed in previous reports. In the new package, the key difference is that one end is open. The opening is approximately two times greater in diameter than in depth; therefore, the soldering of the silicon element to the heat sink prong and the bonding of the top contact is a straight-forward assembly operation.

Various methods of contact were evaluated in order to form a bonded contact. Wire, ribbon and mesh of various widths were evaluated. Numbers of wires and ribbons in parallel were also evaluated. The setup described by Figure 12 was used to measure package inductance. Coaxial mounts were used to accomodate the various package configurations. With the mount open circuited, the probe was set to a maximum position. A solid short of the same geometry as the package to be measured was then inserted into the mount at the former open position. The adjustable short was moved until a minimum was obtained at the probe. This point

served as a reference and was known to be a number of multiple
half wave-lengths away from the shorted package. A package to
be measured was then inserted into the mount, and a new minimum
was obtained with the probe. The shift in probe position, con-
verted to fractions of a wavelength thereby representing the
unknown inductance. The corresponding inductive reactance was
obtained from a Smith Chart. Inductance was then calculated at
the measurement frequency, f_m, from

$$L = \frac{X_L}{2 \pi f_m}$$

To obtain measurements, special packages were assembled
with the semiconductor element excluded. Wires, ribbons and other
possible contact methods were then evaluated by connection directly
to the mounting pedestal. The purpose of the measurements was to
obtain comparative information concerning the relative effect of
the various contact methods upon inductance. The more difficult
question of total inductance, which may depend considerably upon
the holder, does not enter the problem of package redesign. The
results are summarized in Figure 10 for the various mesh widths.
Four wires of five mil diameter were found to be approximately
equal to the mesh. Smaller diameter wires were higher inductance.
Based upon the measured data, it was decided that fifteen mil
2-loop copper mesh or ribbon could be used because of ease of
fabrication combined with reasonable current-carrying capacity.
The inductance of the welded pill III is higher than that of the

axial pill II by 0.2 nanohenry. Pill II, however, has a higher
capacitance. It should be possible to increase the pedestal
height in pill III to lower the package inductance. The pedestal
could be lengthened by an amount sufficient to bring the package
capacitance from 0.18 pf to 0.24 pf like that of axial pill II.

Bonded contact is made to the silicon element basi-
cally by the use of a 15-mil copper mesh or ribbon depending on
capacitance, and the package is sealed hermetically by welding.
This technique has allowed the production of a more reliable
varactor diode.

SECTION V - CONCLUSION

A. There is an apparent frequency dependence of the
series resistance of a varactor diode, but conclusive proof is
difficult to obtain because of several factors. These factors
include circuit losses, capacitance, and skin effects which are
all extremely important in R_s measurement. There is evidence
that indicates that series resistance should be measured in the
vicinity of 1 to 2 Gc to obtain satisfactory results.

B. A silicon monoxide passivation technique has been
developed with subsequent increases in stability and production.
This passivation technique has placed on the surface of the silicon
element a protective layer which protects the surface from con-
tamination.

C. An open pill package assembly has been purchased
in an assembled form. This assembly has allowed the use of a

bonded contact which is much more reliable than a "C" spring contact. The open type construction has allowed a greater ease of fabrication and the welded final seal has provided for a more hermetic package.

SECTION VI - PROGRAM FOR NEXT QUARTER

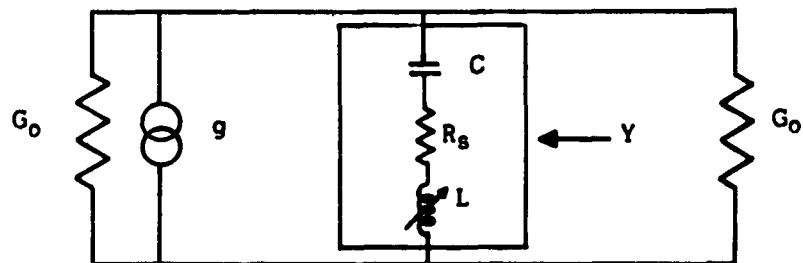In the next quarter more work will be performed on the pill III construction and welding techniques.

SECTION VII - KEY PERSONNEL

		Man Hours
1.	F. Kupriss	70
2.	N. Prasinos	80
3.	D. Revelotis	200
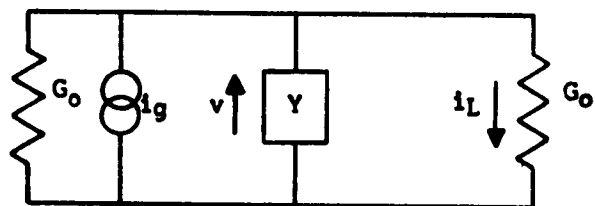
TRANSMISSION LINE

FIGURE 1

ADJUSTABLE SERIES INDUCTANCE

FIGURE 2

SLIDING SHORT

EQUIVALENT IMPEDAN

L

R'

INPUT OF STUB

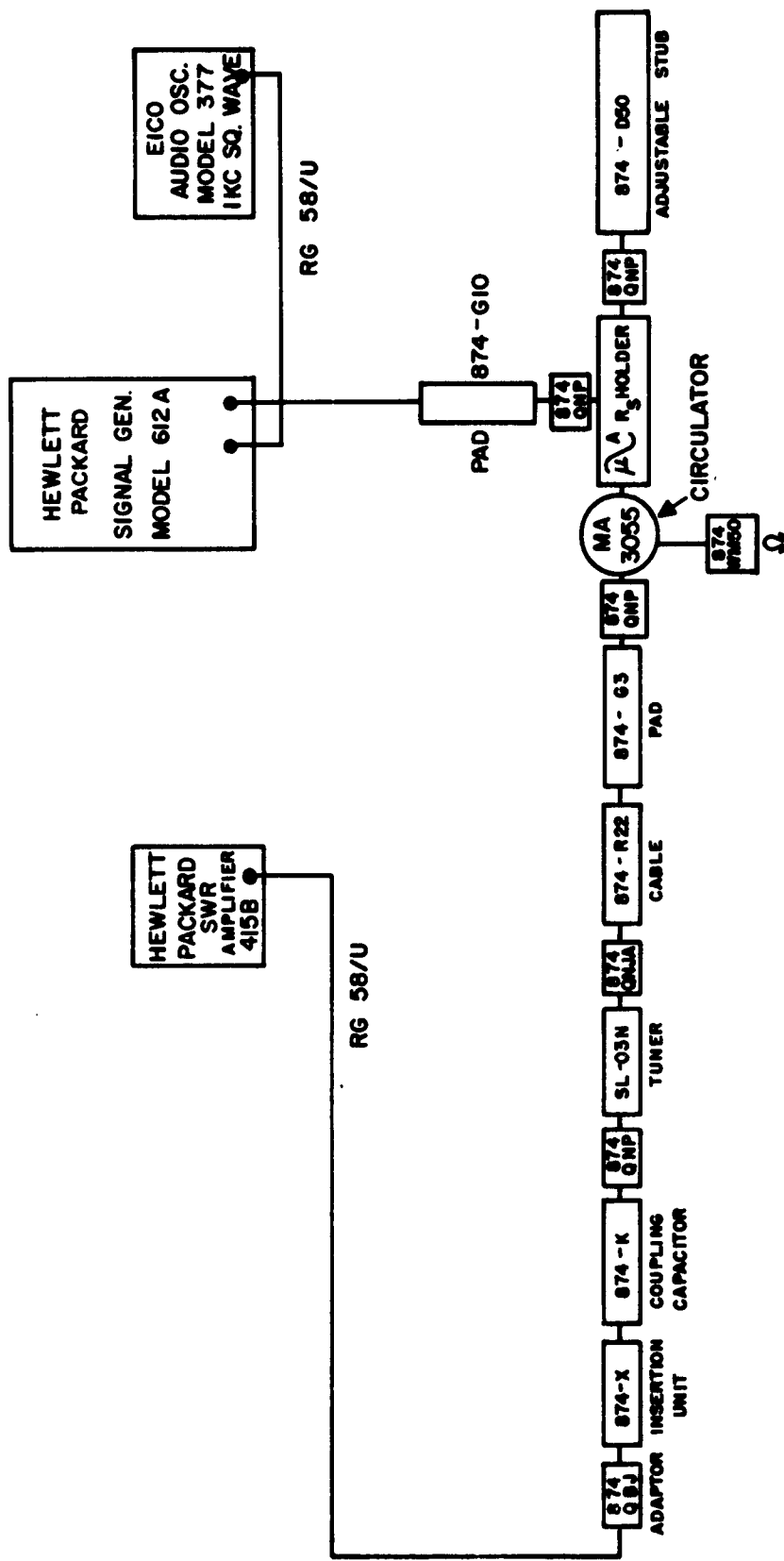LET R_F = FINGER RESISTANCE
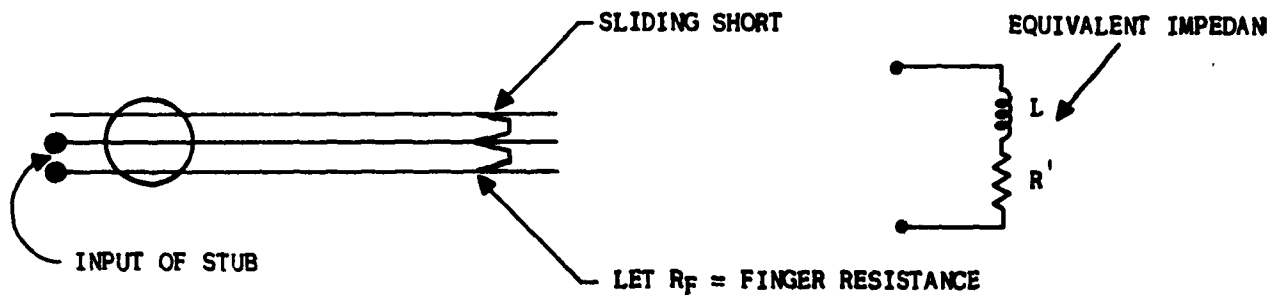
ADJUSTABLE STUB

FIGURE 3
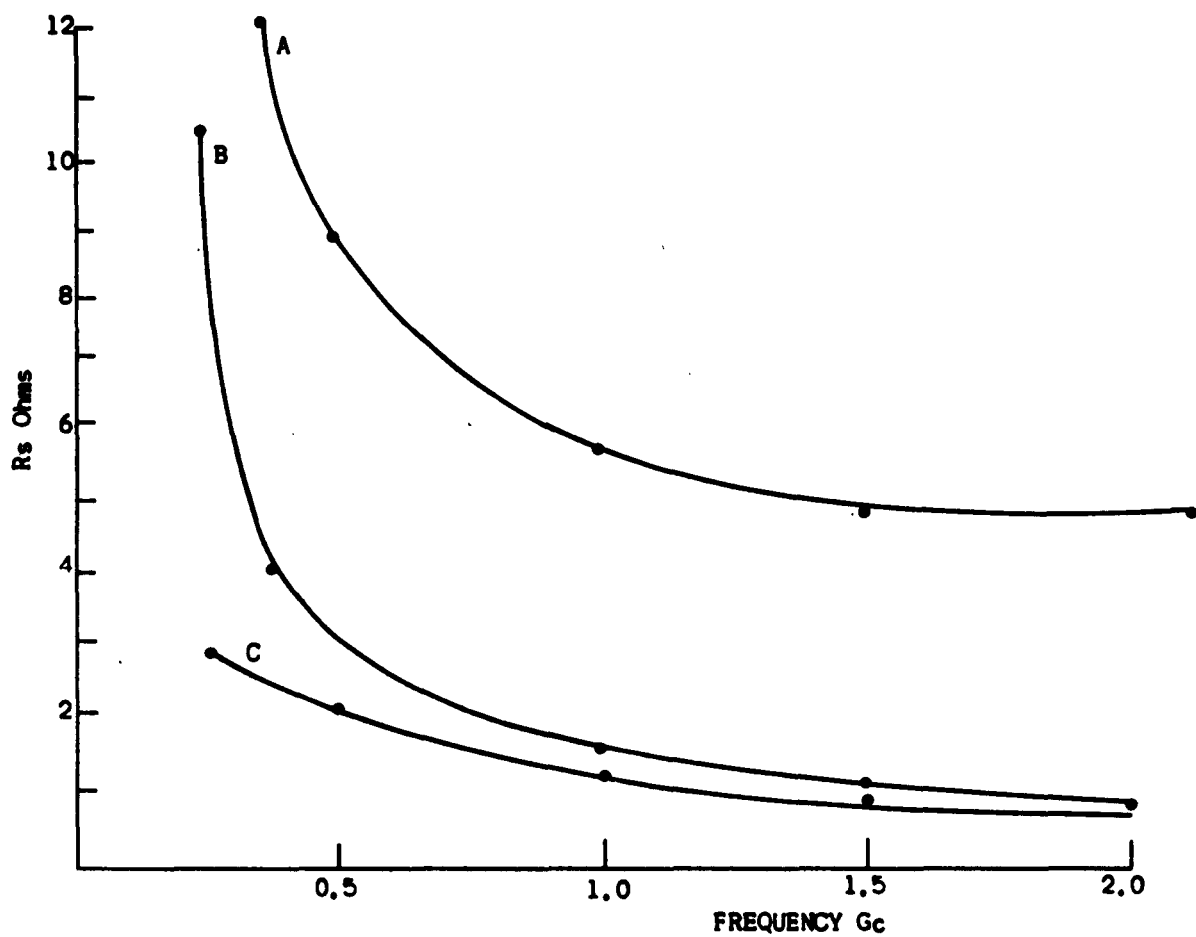
EQUIVLAENT SERIES RESISTANCE vs. FREQUENCY

FIGURE 4

NOTE:

1. ALL 874 TYPES ARE MFG. BY
   GENERAL RADIO CO.

2. SL 03N MFG. BY MICROLAB

FIGURE 5

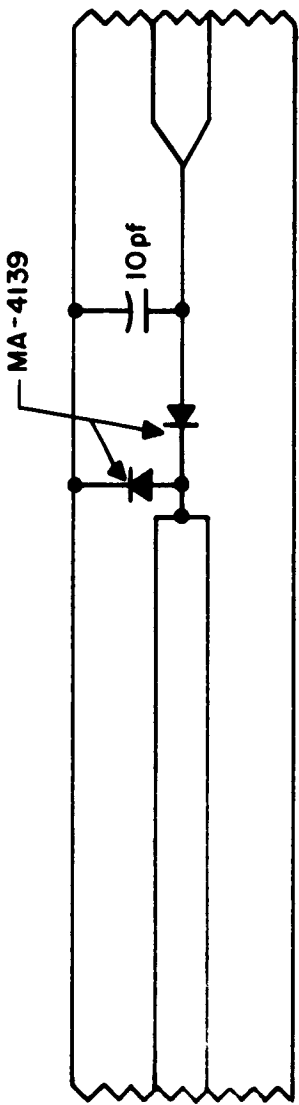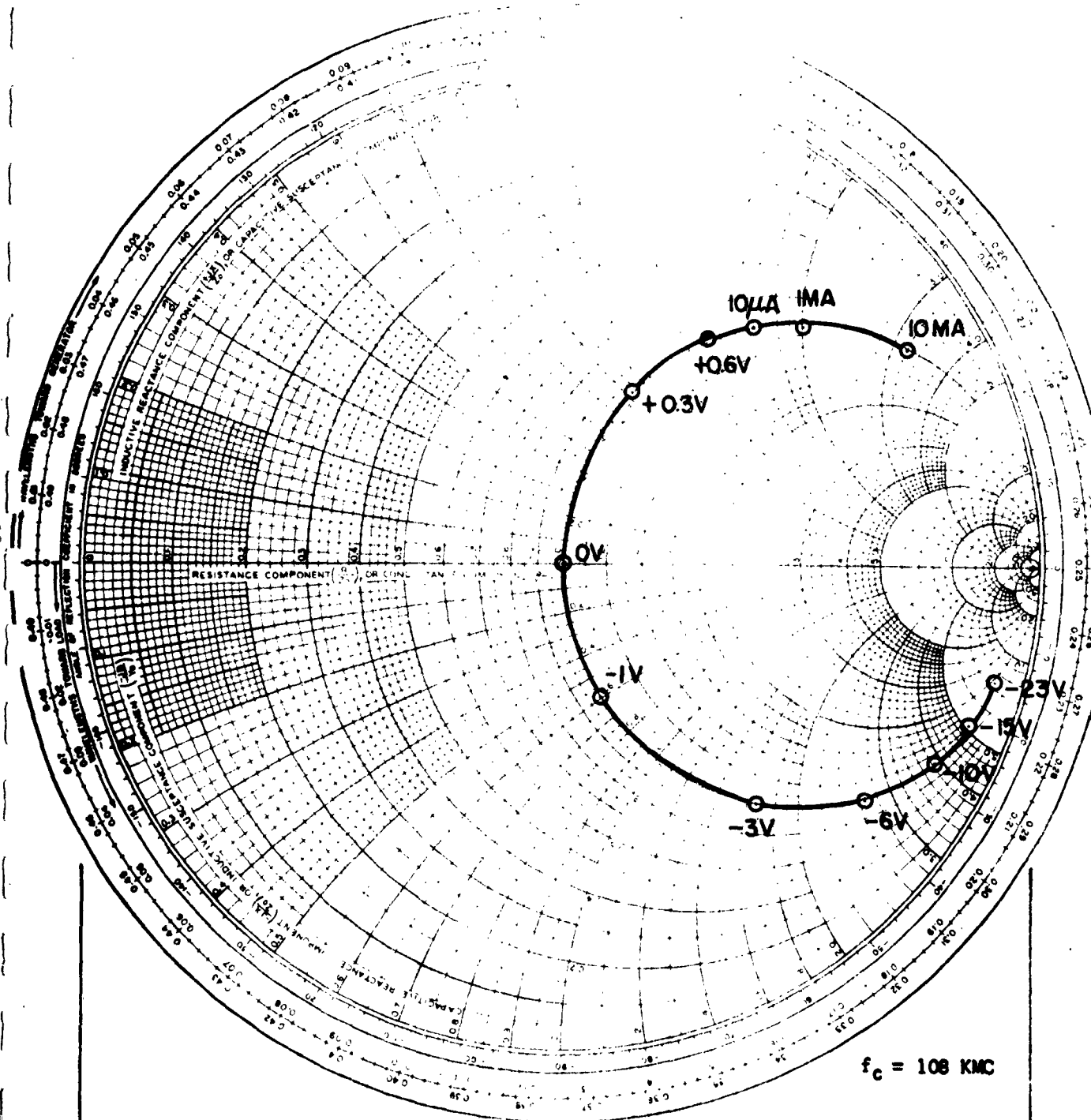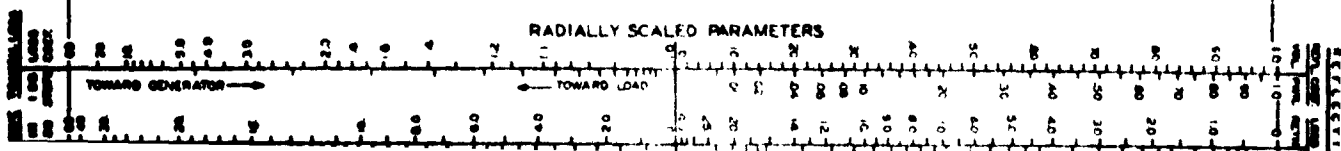BLOCK DIAGRAM FOR SERIES RESISTANCE TEST
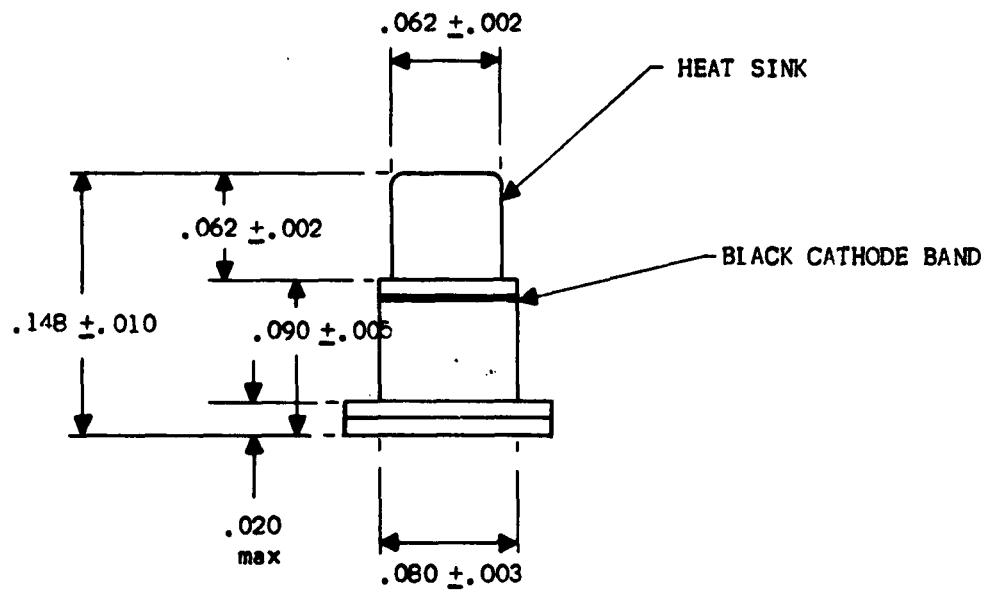
FIGURE 6

DETECTOR CIRCUIT

FIGURE 7

MICROWAVE
10 KMC
IMPEDANCE OR ADMITTANCE COORDINATES

$f_c = 108$ KMC

.062 ±.002

HEAT SINK

.062 ±.002

BLACK CATHODE BAND

.148 ±.010

.090 ±.005

.020 max

.080 ±.003

PILL III

FIGURE 8

.080 ±.002

.062 ±.0005

.008 ±.001

.142 +.003 -.002

.035 ±.002

.060 ±.002

.010 ±.001

.040 ±.001

.050 ±.002

.120 ±.002
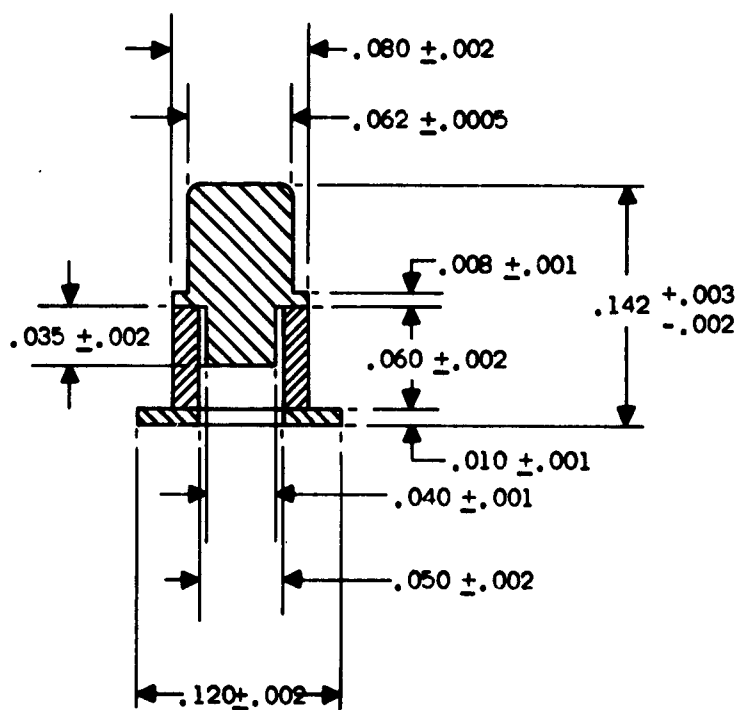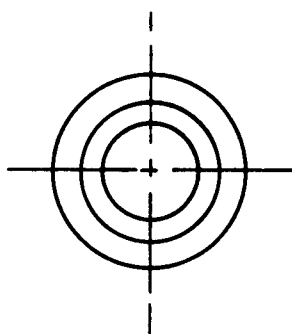
Pill III

FIGURE 9

FIGURE 1C

Comparative Inductances for Pill 111

Standard Pill 11			.225	10^{-9} henries
One	-	one-mil wire	1.02	
Two	-	one-mil wires	.60	
Four	-	one-mil wires	.42	
One	-	five-mil wire	.70	
Four	-	five-mil wire	.36	
One	-	ten-mil mesh	.70	
Two	-	ten-mil mesh	.38	
Four	-	ten-mil mesh	.32	
One	-	fifteen-mil mesh	.67	
Two	-	fifteen-mil mesh	.40	
One	-	twenty-five mil mesh	.60	
Two	-	twenty-five mil mesh	.43	

.062 ±.002 DIA.

.062 ±.004

.142 ±.005

.205 ±.005

COLOR BAND DENOTES
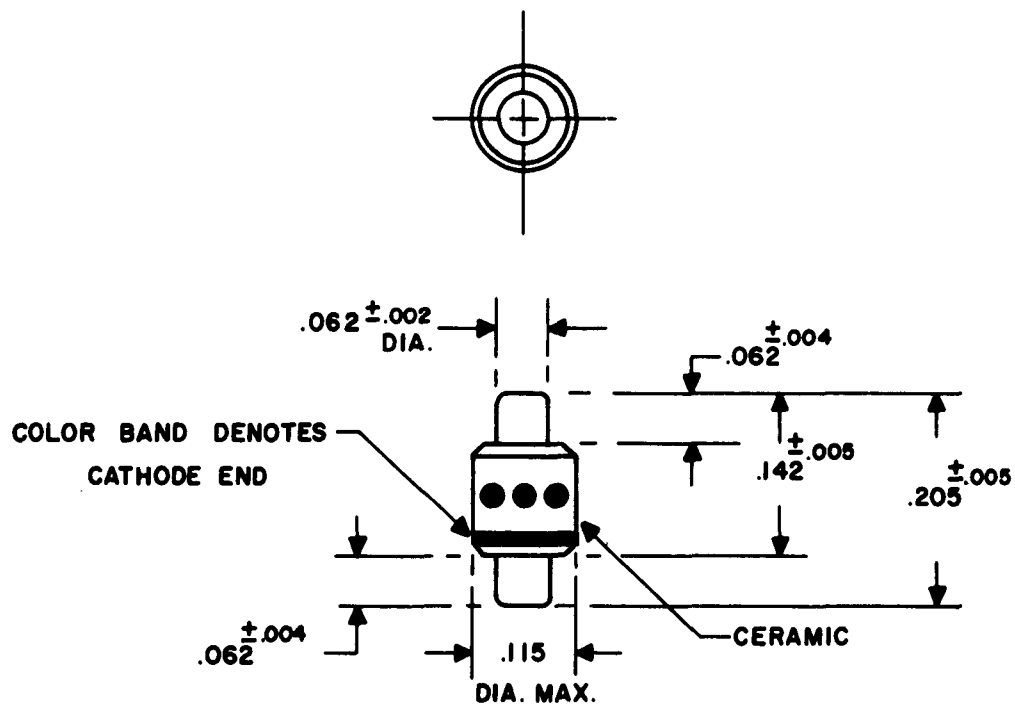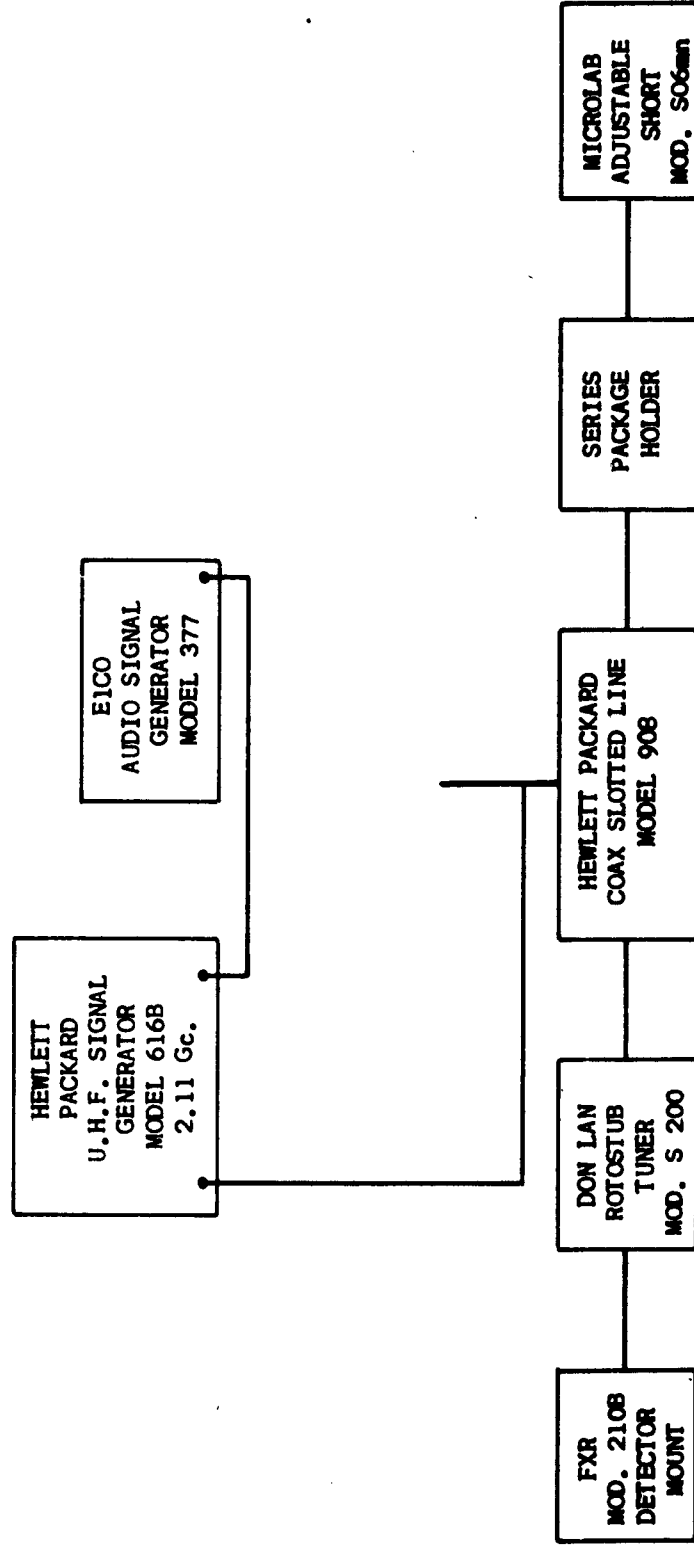CATHODE END

CERAMIC

.062 ±.004

.115
DIA. MAX.

FIGURE II

PILL-WITH-PRONGS VARACTOR CARTRIDGE
PILL II

BLOCK DIAGRAM OF PACKAGE INDUCTANCE TEST

FIGURE 12